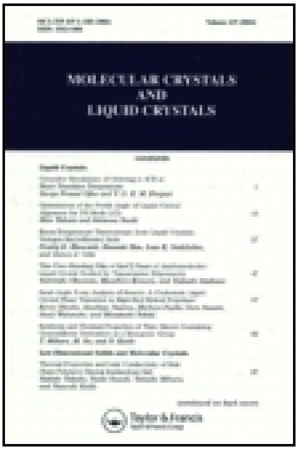

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Phase Retarder LCDs†

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Interference colors produced by birefringent plastic layers can be used in conjunction with the twisted nematic liquid crystal displays to produce attractive blue vs. gold LCDs when viewed in reflection. Brightness of the retarder LCD is maximized by using low tilt angle alignment, thin glass on the rear of the display and a full reflector.

INTRODUCTION

This paper discusses the use of a plastic, birefringent layer exterior to the twisted nematic display to produce an attractive blue vs. "gold" LCD when viewed in reflection. The possibility of interference colors with LCD has been known for some time, especially in very thin liquid crystal layers.[1] Colors resulting from ordinary and extraordinary modes in the liquid crystal are difficult to control due to the thickness uniformity which is required to make the optical path length the same all over the display. Scheffer[2] showed how the color could be controlled better when the interference effects took place in a piece of birefringent plastic exterior to the liquid crystal layer. It is much easier to control the birefringence properties of the plastic than the liquid crystals.

SCHEFFER'S GEOMETRY

The experimental arrangement is shown in Figure 1. The geometry is essentially that proposed by Scheffer with the exception that the retarder in Figure 1 is in front of rather than behind the cell. The twisted nematic cell is prepared with its orientation directions in the x-y directions with light propagating through the cell in the z direction. A front polarizer is oriented to pass polarized light with polarization in the x direction and a rear polarizer passes light polarized in the y direction. The phase retarder is placed between the front

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polarizer and the cell with the retarder's optic axis (OA) at 45° to the x axis. The retarder is a layer of polyvinyl alcohol stretched to achieve a birefringence Δn in a thickness d with a consequent retardation Δnd. Without the retarder, the display looks like a standard twisted nematic—dark numbers on a gray field.

The phase retarder display produces complementary colors in the following manner. The polarized light incident on the phase retarder produces both ordinary ($E \perp OA$ $E =$ light polarization) and extraordinary ($E \| OA$) modes in the retarder. These two modes emerge with different phases, and the light is consequently elliptically polarized. The light passes through the cell and the x and y components are both twisted by 90°. The light emerges elliptically polarized with the major axis of the ellipse twisted 90°. When the light now crosses the rear polarizer, interference color results. The birefringence of the LCD is not detected because the analyzer detects only one mode of the cell, the mode with light linearity polarized in the x direction at the front of the cell.

EARLY REFLECTIVE EXPERIMENTS

Scheffer discussed the case of transmissive color thoroughly, but stated that reflective viewing, i.e., Figure 1 plus a mirror was inferior. He attributed the dark appearance of the reflective display to pseudodepolarization produced by the twisted nematic cell.

Shanks[3] showed how bright colors could be obtained in reflection by eliminating the rear polarizer and by using a diffuse metal reflector. The liquid crystal display in Ref. 3 was a 45° twist cell as opposed to the traditional 90° twist cell. While this display appears brighter, the elimination of the rear polarizer significantly degrades the viewing angle of the display.

In a British patent[4] Shanks discussed the two polarizer reflective design (90° twist) which Scheffer discounted as being too dark. Shanks emphasized that a diffuse metallic reflector is preferable for brightness over a white paper reflector. He did not comment on Scheffer's remark that the two polarizer reflective display is too dark. Shanks noted that the reflective colors are more saturated in the two polarizer geometry due to the two independent passes through the display.

CURRENT REFLECTIVE EXPERIMENTS

The remainder of this paper will disucss efforts to improve the appearance of the phase retarder display. The basic design is shown in Figure 2. The design is similar to the reflective display in Shank's patent with the exception that the

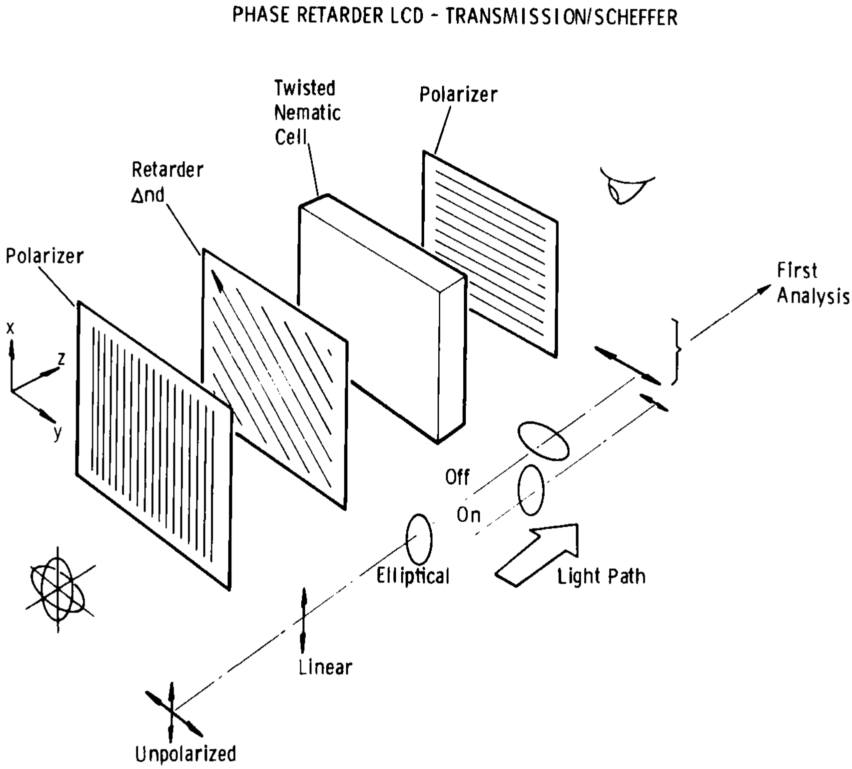

FIGURE 1 Phase Retarder LCD in Transmission. A schematic representation of the phase retarder LCD is shown. Unpolarized light is converted into linearly polarized light by the front polarizer. The optic axis of the retarder is oriented at 45° to the axis of the polarizer so that equal amplitudes of ordinary and extraordinary waves are launched in the retarder. Elliptically polarized light emerges and enters a standard twisted nematic cell. If the cell is "off" the major axis of the ellipse is twisted 90°. If it is "on", the ellipse is transmitted unchanged. The rear polarizer analyzes the ellipticity of the various wavelengths present in ambient light into interference colors seen by the observer behind the cell. Note that the retardation of the twisted nematic cell is not detected since the axis of the rear polarizer is placed parallel (or perpendicular) to the alignment direction at the rear of the cell.

retarder is on the viewer's side of the display rather than on the mirror side. The significance of this will be explained below. The light entering the display is modulated the same way as was discussed above. A mirror is added which does not depolarize the linear polarized light leaving the rear polarizer. The mirror reflects the polarized light back through the rear polarizer which passes most of the reflected light. Forty-eight percent transmissive polarizers were chosen to enhance the overall brightness of the cell.

The linear polarized light passes once again through the liquid crystal and is twisted 90°. Once again the retarder propagates two modes of equal ampli-

PHASE RETARDER LCD - REFLECTION

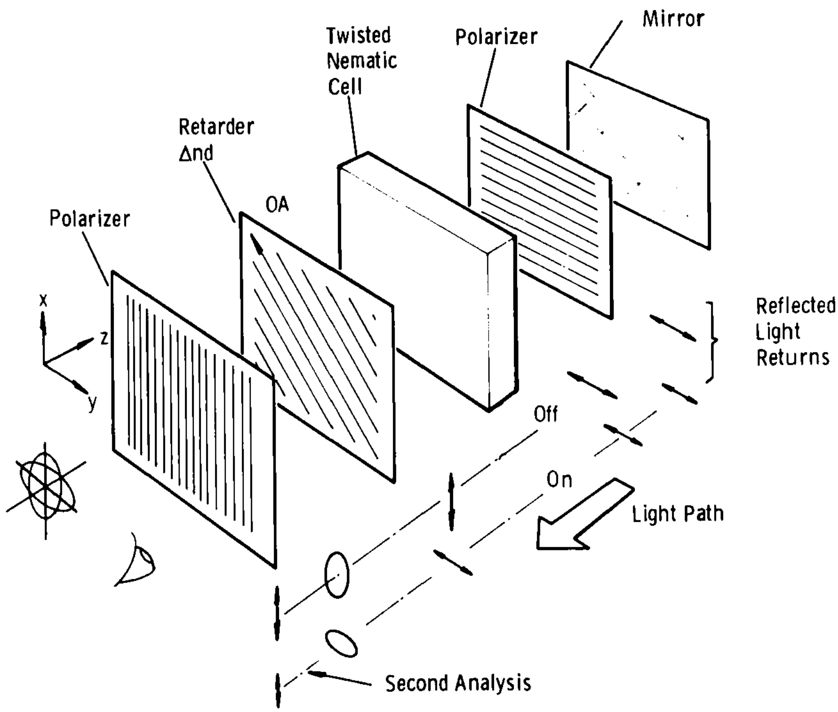

FIGURE 2 Phase Retarder LCD in Reflection. The light reaches the reflector as shown in Figure 1. The reflected light is linearly polarized and passes through the rear polarizer with very little attenuation. The cell rotates the linear polarization if "off" and passes it directly if "on". The linear polarization is again transformed into a wavelength sensitive ellipticity which is analyzed a second time by the front polarizer. Since the light has passed through the cell twice independently, the reflection function is related to the square of the single pass transmission function. More saturated color results.

tude but with a color bias due to the first pass through the system. The ordinary and extraordinary modes are again phase shifted by different amounts, and an elliptically polarized wave train emerges. This wave train is analyzed by the front polarizer and the color content is enhanced. The reflection function is in effect the transmission function squared. This sharpens the function and results in more saturated colors.

Figure 3 shows two examples of the colors obtained with $\Delta nd = 1\lambda$ phase retarder material. The display on the right is made with crossed polarizers as in Figure 2. The display on the left is made with parallel polarizers which reverses the color contrast. With crossed polarizers the display is blue digits on a pleasant gold field. With parallel polarizers the digits are yellowish on a strik-

FIGURE 3 Phase Retarder Displays. Operating phase retarder displays are shown in stainless steel and gold cases. On the right hand side the polarizers on the display are crossed as in Figure 2. Blue letters on a gold field results. On the left hand side the polarizers are parallel producing gold letters on a blue field. The blue field is visually very pleasing, but the off axis contrast is inferior as is the case with all parallel polarizer cells. The fidelity of the colors can be judged relative to the familiar colors of the stainless steel and gold cases and bracelets. The optical retardation for both examples was $\Delta nd = 1\lambda$. The details of the display construction are described in the text.

ing royal blue field. Unfortunately, this latter display lacks a broad viewing area since the bright state comes from the homeotropic liquid crystal texture. This effect is well known from standard liquid crystal technology.

There are several keys to maximizing the aesthetics of the phase retarder LCD viewed in reflection. *First,* the phase retarder must have the optic axis in the plane of the plastic films. This was realized by Scheffer and results in a broad cone of equal color modulation. *Second,* the uniformity is preserved by using a twisted nematic cell which has a low tilt angle alignment. Low tilt angle alignment leads to more uniform conoscopic figures than high tilt angle alignment, and this again results in more uniform color viewing. *Third,* the reflector should be a total mirror rather than a transflector, or partially transmitting reflector used for backlight displays. The transflectors sacrifice a significant amount of daylight brightness to achieve night time backlighting. The phase retarder displays can not afford this luxury.

The importance of the first three items were established in the literature by the time this work was begun. This work has established the utility of two additional design features. *Fourth,* the polarizers should be of the highly transmissive type, e.g., 48%. This softens the traditional contrast somewhat, but the color contrast makes up some of the difference, and the increased brightness is essential. Naturally, the polarizers and retarders should be of high quality.[6] *Fifth,* it is very useful to have the mirror as close to the liquid crystal layer as possible. This is because of the "double image" quality of the twisted nematic display.[5] The display looks best if the real and mirror images appear very close together. The phase retarder display, which is just a color selective twisted nematic shows the same effect. The display in Figure 3 have 250 μm glass back plates—up to one third the thickness of the back glass in most commercial displays. Also, the phase retarder plastic was placed on the viewers side of the display. Placing it on the back side of the display would have unnecessarily added to the thickness and spoiled the "single image" appearance.

Tests have been made with other optical thickness phase retarder material. $\Delta nd = 1\ 1/4\lambda$ material results in a purple on green display. $\Delta nd = 1\ 1/2\lambda$ material results in a reddish brown on blue green. By far, the best results are with the $\Delta nd = 1\lambda$ retarder of the three tests since the gold background was the brightest. In theory, any two complementary interference colors can be achieved. For a discussion of interference see Hartshorn & Stuart.[7]

Since multiplexing LCDs in a topic of intense interest currently, it is relevant to ask if the color contrast adds to or detracts from the sharpness of the threshold. Unfortunately, color perception is a very personal subject. It appears to the author that there is not any significant enhancement in ambient reflection. Bigelow, *et al.*,[8] have discussed using phase retarders for projection display LCDs.

CONCLUSION

The phase retarder LCD can give interesting, saturated color LCDs when viewed in reflection. This is especially true at $\Delta nd = 1\lambda$ and less so at higher retardation. The colors are appealing when compared with state-of-the-art dye displays, contrary to the general impression contained in the early 1970s literature. Several design rules must be followed to achieve adequate brightness, especially having a thin back glass on the display.

Acknowledgment

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